Physics at e^+e^- Linear Colliders

1. e^+e^- annihilation to pairs

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Over the past year, there has been much debate, both in the US and in the world community, about the next major accelerator for high-energy physics.

Advisory groups in all of the major regions have now declared that the proper next step is the construction of a

500 GeV e^+e^- Linear Collider

The location of this accelerator is still to be decided, but Fermilab is an obvious choice.

For you, this is good news:

With all the world's regions working together, we might indeed have - 10 years from now - a new accelerator at which you can do experiments.

It is not too early to begin planning your physics program for this machine.

What do you need to know ?

The purpose of the LC is to study physics beyond the Standard Model, but, to understand how to do this, you first have to understand the Standard Model deeply.

This is especially true in thinking about experiments at the LC.

At the time of the LC experiments, the LHC will already be operating at a higher energy.

The LC experiments must rely on high precision measurements and an environment that allows a detailed undertstanding of the physics.

In these lectures, I will present tools for understanding the physics of e+e- annihilation at high energy. I willl discuss the expected behavior of the Standard Model and, from this reference point, some possibilities for new physics.

More specifically, I will cover :

1. e^+e^- annihilation to pairs

2. W and t

3. Higgs bosons

4. Supersymmetry

Many of the effects I will describe are modeled at the parton level by my simulation program pandora.

This is available at the URL:

http://www-sldnt.slac.stanford.edu/nld/new/Docs/Generators/PANDORA.htm

or by following the links from my home page:

http://www.slac.stanford.edu/~mpeskin/

Please take the opportunity to play with this code; it may give you a better feel for the physics presented in this course.

From LEP/SLC/Tevatron, we know that Nature really does contain an SU(3)XSU(2)XU(1) gauge theory describing strong, weak, and electromagnetic interactions.

measured Z^0 parameters and m_W agree with the SM to high precision, with a universal $\sin^2\theta_W$

$WW\gamma$, WWZ couplings measured at LEP 2 agree with the prediction from Yang-Mills theory

SU(2)XU(1) must be spontaneously broken, but this symmetry becomes apparent at high energy.

So, use SU(2)XU(1) quantum numbers to classify familiar and exotic particles.

In the SM, all particles have quantum nos. (I, I^3, Y)

Before symmetry breaking,

W_μ^0 couples to I^3 w. strength g

B_μ couples to Y w. strength g'

$$g = \frac{e}{\sin\theta_w} \qquad g' = \frac{e}{\cos\theta_w}$$

After symmetry breaking,

A_μ couples to $Q = I^3 + Y$ w. strength e

Z_μ couples to $Q_Z = (I^3 - \sin^2\theta_w Q)$ w. strength $\dfrac{e}{\sin\theta_w\cos\theta_w}$

$$m_W^2 = \frac{g^2}{4}v^2 \qquad m_Z^2 = \frac{g^2 + g'^2}{4}v^2 \qquad v = 246\ \mathrm{GeV}$$

Using this language, we can discuss e+e- annihilation to various species in great generality.

The standard form of a cross section is

$$\frac{d\sigma}{d\cos\theta} = \frac{1}{2s}\cdot\frac{1}{16\pi}\cdot\frac{1}{4}\sum_{pol}|\mathcal{M}|^2$$

At the LC, it is possible

- to produce polarized e^- beams
- to observe the polarization of many final states

so, I will work with amplitudes for particles with definite polarization.

$$\mathcal{M} = e^2 M$$

then

$$\frac{d\sigma}{d\cos\theta} = \frac{\pi\alpha^2}{2s}|M|^2$$

Using $\alpha \sim 1/128.$

we can estimate: $$\frac{\pi\alpha^2}{2s} = 150 \text{ fb} \cdot \left(\frac{500 \text{ GeV}}{E_{\text{CM}}}\right)^2$$

In e+e- annihilation, all particles, familiar and exotic, are produced with roughly this cross section.

With luminosity samples of 100 fb^{-1}, we can produce 10,000 events, with signal and background processes at the same level before cuts.

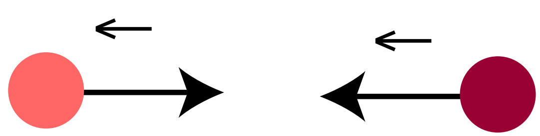
In this situation, we can use all relevant final states, and reconstruct complete events.

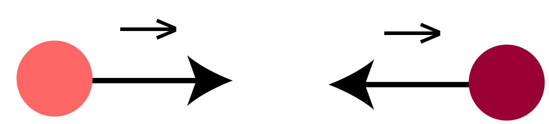
More specifically, consider the amplitude for e^+e^- annihilation to boson pairs. In pure QED:

$$i\mathcal{M} = ie^2 \cdot \sin\theta \cdot s \cdot \left(\frac{-1 \cdot Q}{s}\right)$$

The particle-antiparticle pairs that annihilate are:

$e^-_L\, e^+_R$ and $e^-_R\, e^+_L$

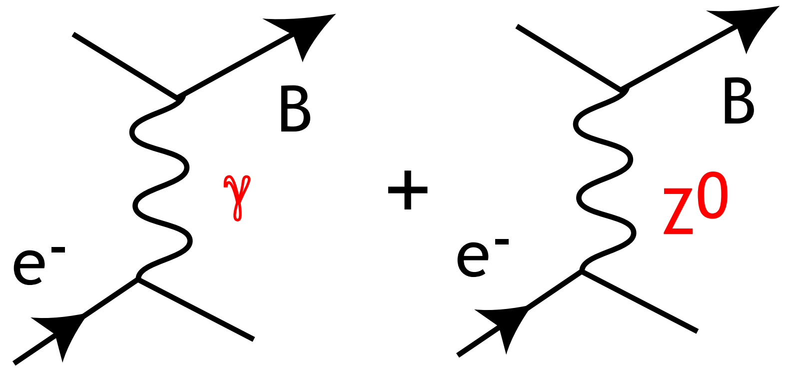




This leads to an intermediate state with $J^z = \pm 1$, hence the characteristic angular distribution.

$$\frac{d\sigma}{d\cos\theta} = \frac{\pi\alpha^2}{2s} \sin^2\theta \, |f_{IJ}|^2$$

Now add γ- Z interference:



$$\frac{f_{IJ}}{s} = \left[\frac{QQ'}{s} + \frac{(I^3 - Qs_w^2)(I^{3\prime} - Q's_w^2)}{c_w^2 s_w^2}\frac{1}{s - m_Z^2}\right]$$

$$= I^3 I^{3\prime}\left(\frac{1}{s} + \frac{c_w^4}{c_w^2 s_w^2}\frac{1}{s - m_Z^2}\right) + (I^3 Y' + I^{3\prime} Y)\left(\frac{1}{s} - \frac{c_w^2 s_w^2}{c_w^2 s_w^2}\frac{1}{s - m_Z^2}\right)$$

$$+(YY')\left(\frac{1}{s} + \frac{s_w^4}{c_w^2 s_w^2}\frac{1}{s - m_Z^2}\right)$$

$$\rightarrow I^3 I^{3\prime}\,\frac{e^2}{s_w^2}\,\frac{1}{s} + YY'\,\frac{e^2}{c_w^2}\,\frac{1}{s}$$

This formula can have large polarization dependence:

Here are values of $|f|^2$ for $e^+e^- \to B^+B^-$

	H^+ w. $I^3 = \frac{1}{2}$, $Y = \frac{1}{2}$	S^+ w. $I^3 = 0$, $Y = +1$
e^-_L	1.98	0.42
e^-_R	0.42	1.69

For e^+e^- annihilation to fermions, we must take account of the final state fermion polarization. Today, treat all fermions as massless. (I will discuss top tomorrow.)

In QED,

$$\frac{d\sigma}{d\cos\theta}(e^-_L e^+_R \to f_L \overline{f}_R) = \frac{\pi\alpha^2}{2s}(1+\cos\theta)^2$$

$$\frac{d\sigma}{d\cos\theta}(e^-_L e^+_R \to f_R \overline{f}_L) = \frac{\pi\alpha^2}{2s}(1-\cos\theta)^2$$

and the reverse for $e^-_R\, e^+_L$. This simply reflects angular momentum conservation:

To describe the SM, replace (-Q) with f_{IJ}:

$$f_{LL} = \left[-1 \cdot Q + \frac{(-\frac{1}{2} + s_w^2)(I^3 - Q s_w^2)}{c_w^2 s_w^2} \frac{s}{s - m_Z^2}\right]$$
$$f_{LR} = \left[-1 \cdot Q + \frac{(-\frac{1}{2} + s_w^2)(-Q s_w^2)}{c_w^2 s_w^2} \frac{s}{s - m_Z^2}\right]$$
$$f_{RL} = \left[-1 \cdot Q + \frac{(s_w^2)(I^3 - Q s_w^2)}{c_w^2 s_w^2} \frac{s}{s - m_Z^2}\right]$$
$$f_{RR} = \left[-1 \cdot Q + \frac{(s_w^2)(-Q s_w^2)}{c_w^2 s_w^2} \frac{s}{s - m_Z^2}\right]$$

Notice that f_{LL} and f_{LR} have constructive interference,
f_{LR} and f_{RL} have destructive interference;

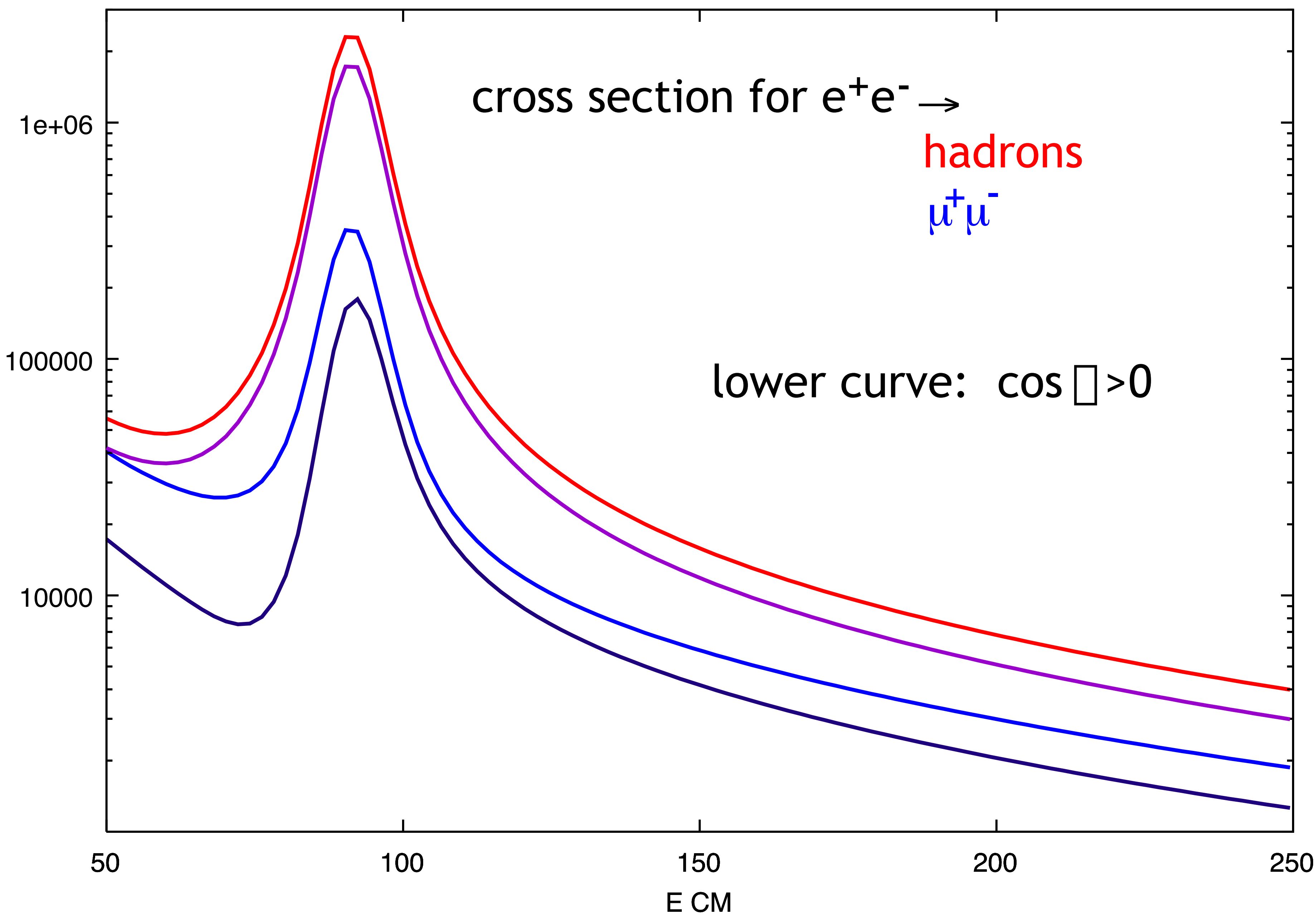
since L fields couple most strongly to W^0, R fields to B.

The asymptotic values of $|f|^2$ vary wildly:

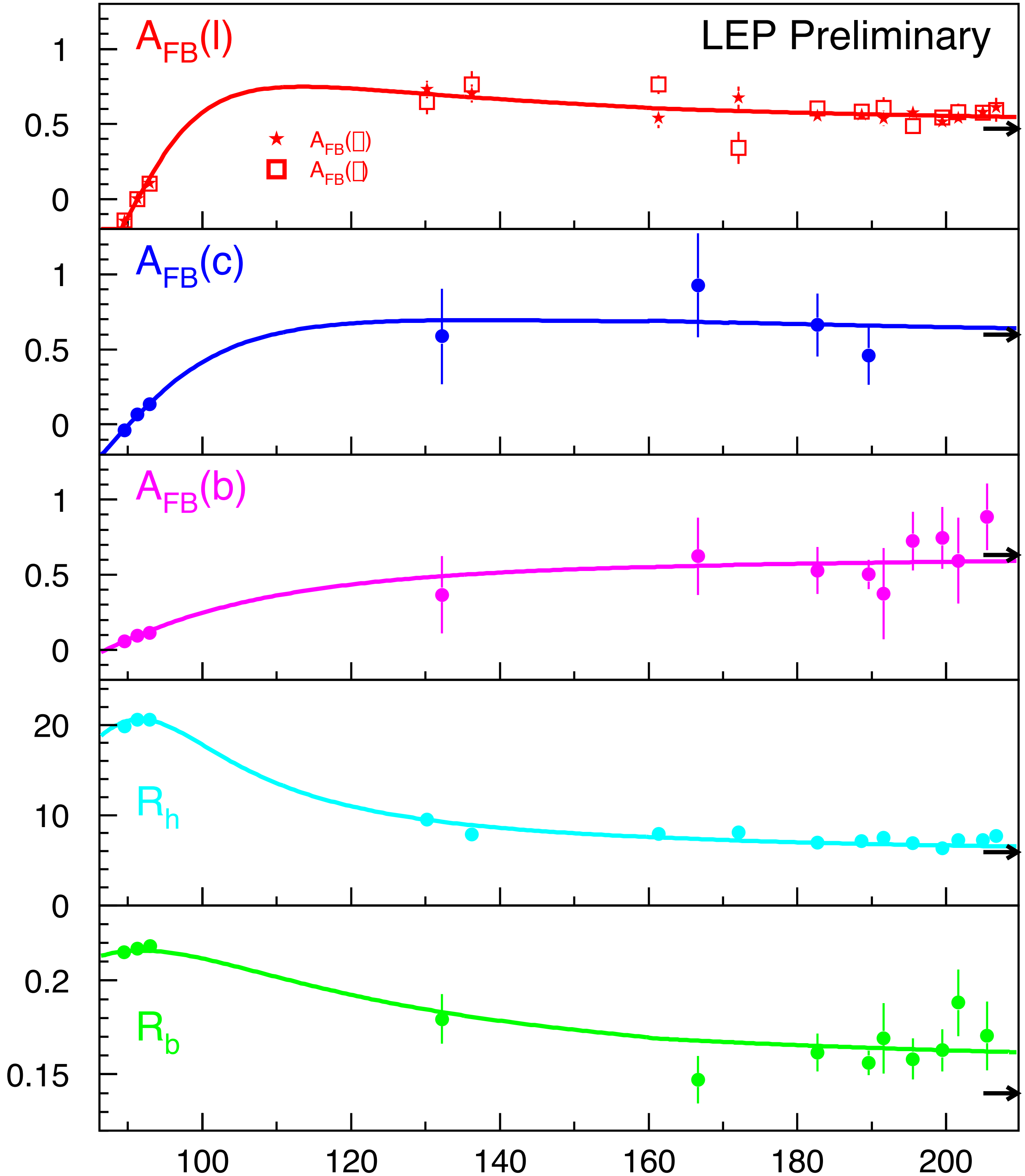
leptons	l_L	l_R	ν_L	
e^-_L	1.98	0.42	0.57	
e^-_R	0.42	1.69	0.42	
quarks	d_L	d_R	u_L	u_R
e^-_L	0.95	0.05	1.42	0.19
e^-_R	0.05	0.19	1.05	0.75

($\cdot\, 3\,(1 + \frac{\alpha_s}{\pi} + \cdots)$ for color)

This generates structure in the patterns of cross sections, polarization asymmetries, and forward-backward asymmetries.



cross section for e+e- →
hadrons
μ+μ-
lower curve: cos >0
1e+06
100000
10000
50
100
150
200
250
E CM



LEP Preliminary
$A_{FB}(l)$
$A_{FB}(c)$
$A_{FB}(b)$
R_h
R_b
1
0.5
0
20
10
0.2
0.15
100
120
140
160
180
200

Hildreth

Additional observables expose more of this structure:

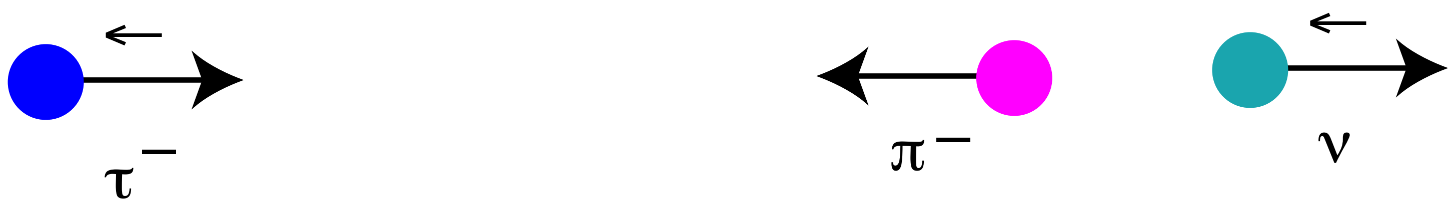
b, c flavor can be identified from the characteristic lifetime and vertex mass

expect 90% efficiency for detection of b vertices

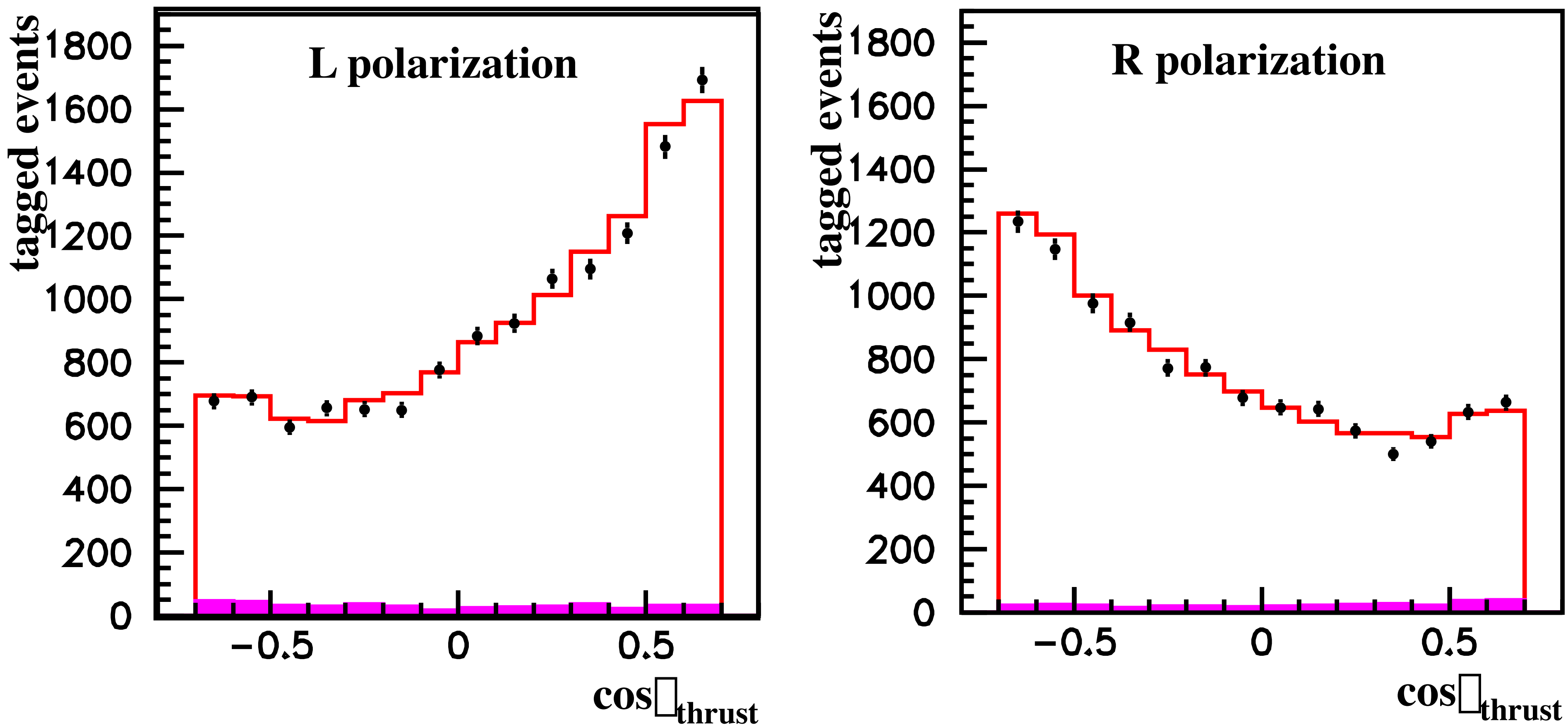
τ decays are sensitive to polarization

e.g.,

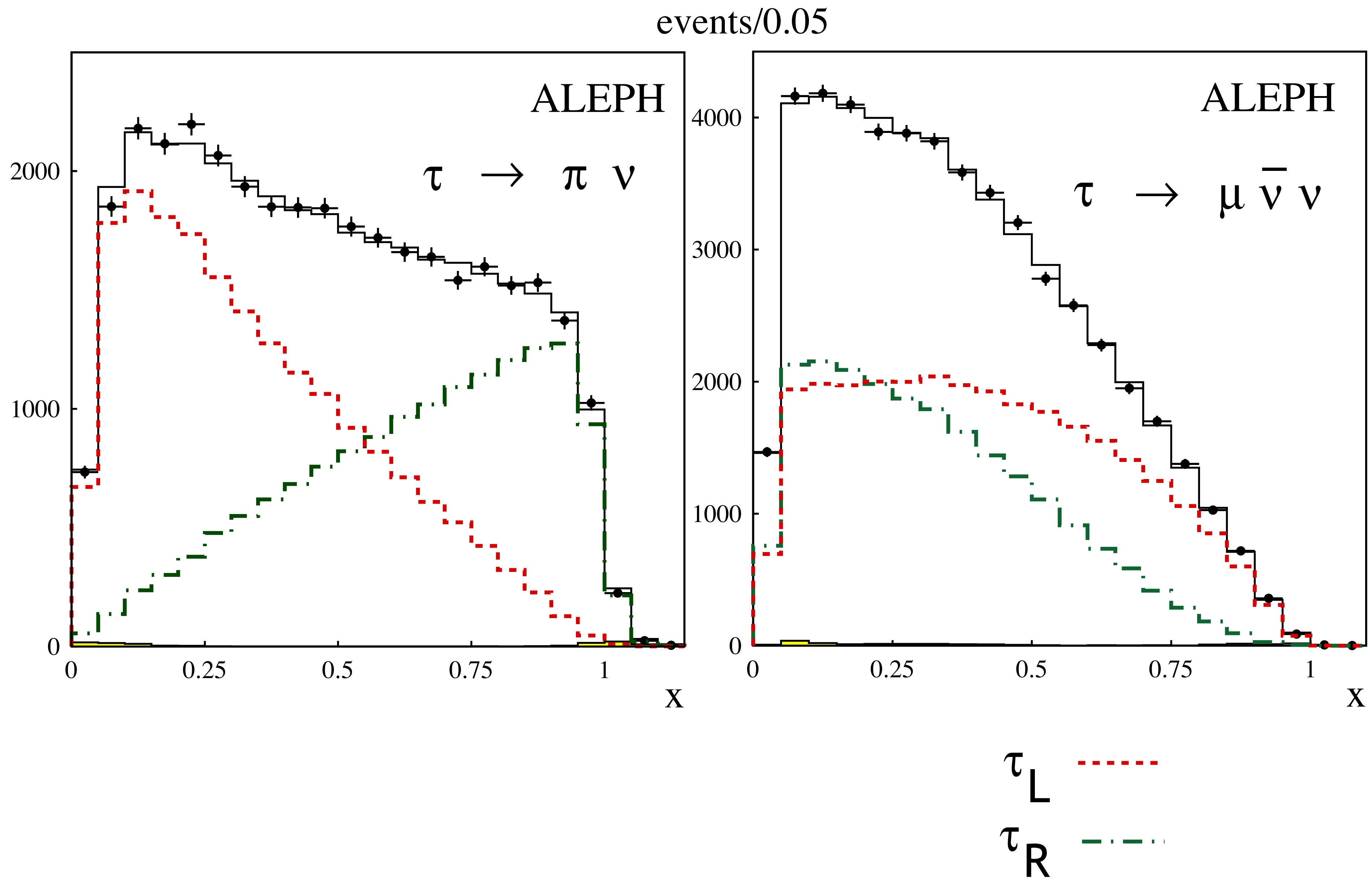
$$\frac{d\Gamma}{dx}(\tau^- \to \pi^- \nu_\tau) \sim \begin{cases} (1-x) & (\tau_L^-) \\ x & (\tau_R^-) \end{cases}$$



e+e- $\rightarrow$ b $\bar{b}$ at SLD



(A_b = 0.94 at the Z^0)


events/0.05
ALEPH
τ → π ν
2000
1000
0
0
0.25
0.5
0.75
1
x
ALEPH
τ → μ ν̄ ν
4000
3000
2000
1000
0
0
0.25
0.5
0.75
1
x
τ_L
τ_R

Now add a little more realism.

Study $e^+e^- \to \mu^+\mu^-$ at 500 GeV,

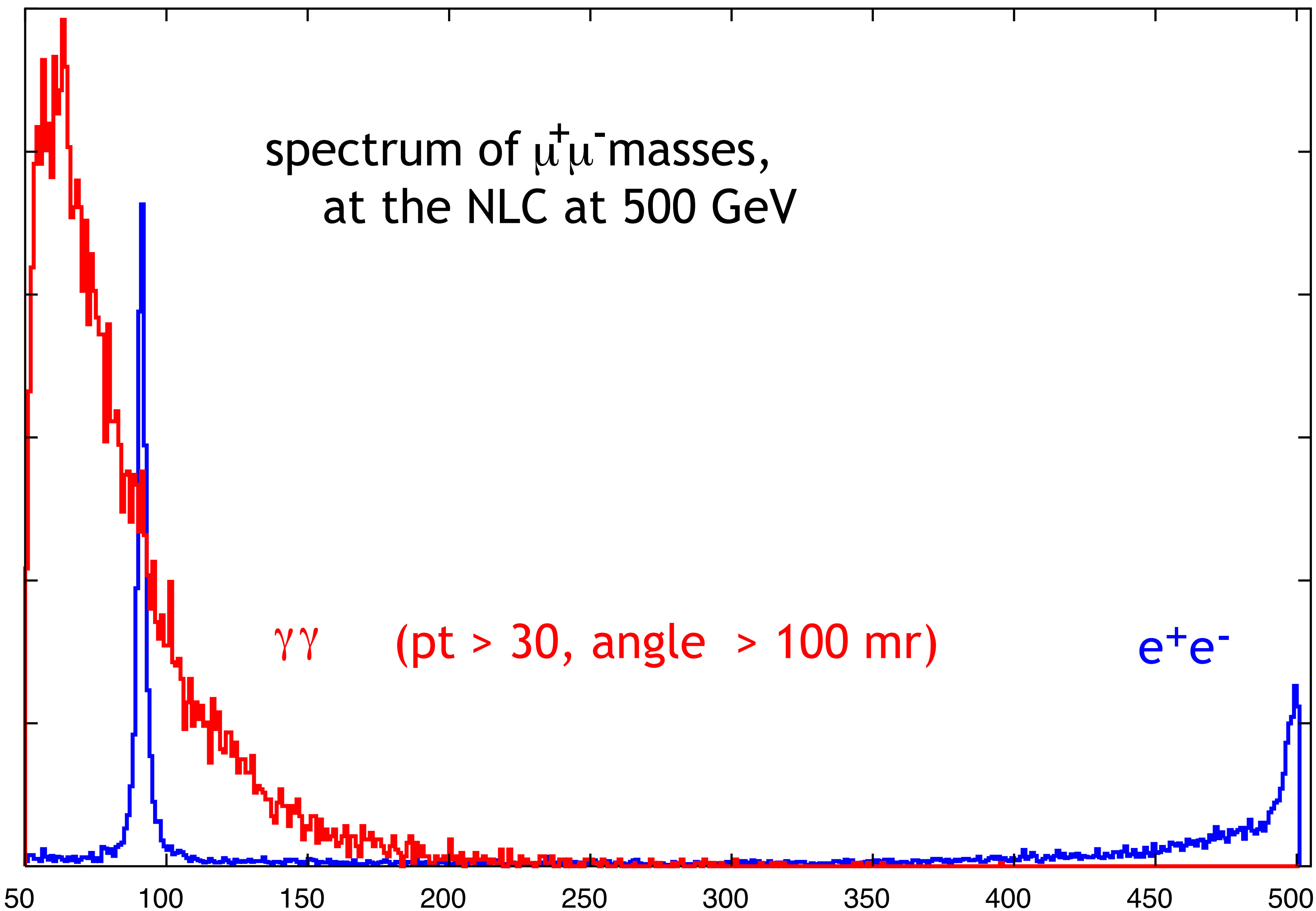
plot the mass of the $\mu^+\mu^-$ system.

Radiation effects are important. We must consider:

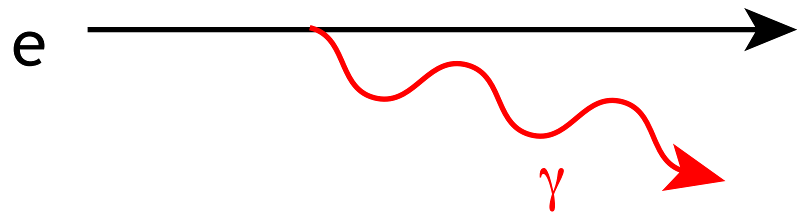
QED radiation in the annihilation process
(bremsstrahlung)

radiation in the beam-beam interaction
(beamstrahlung)

photon-generated backgrounds such as $\gamma\gamma \to \mu^+\mu^-$


spectrum of μ+μ- masses,
at the NLC at 500 GeV
γγ
(pt > 30, angle > 100 mr)
e+e-
50
100
150
200
250
300
350
400
450
500

initial-state radiation (ISR):



radiating one photon gives the electron a distribution in longitudinal fraction x:

$$f_e(x) = \delta(1-x) + \frac{\alpha}{2\pi}\log\frac{s}{m_e^2}\left[\frac{1+x^2}{(1-x)_+} + \frac{3}{2}\delta(1-x)\right]$$

the log comes from integrating over a p_T distribution:

$$\int \frac{d^2 p_T}{(2\pi)^2}\,\frac{1}{p_T^2}$$

radiating many photons leads to the structure function:

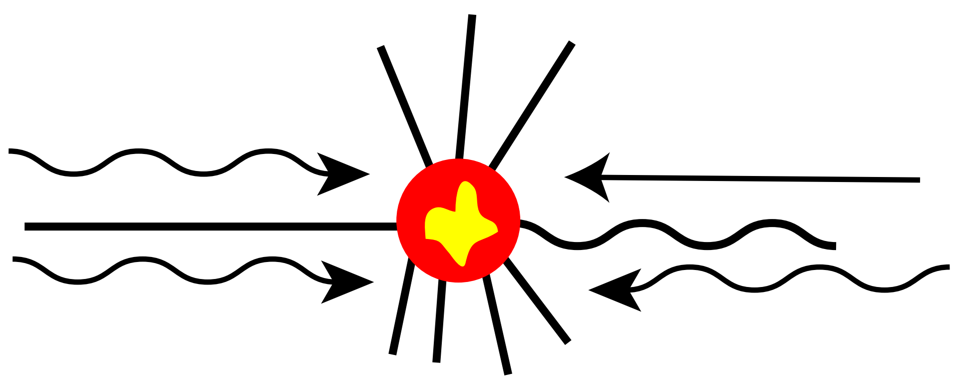
$$f_e(x) = \frac{\beta}{2}(1-x)^{\beta/2-1}\left(\frac{1+x^2}{2} + \mathcal{O}(\beta)\right)$$

Fadin-Kuraev

where

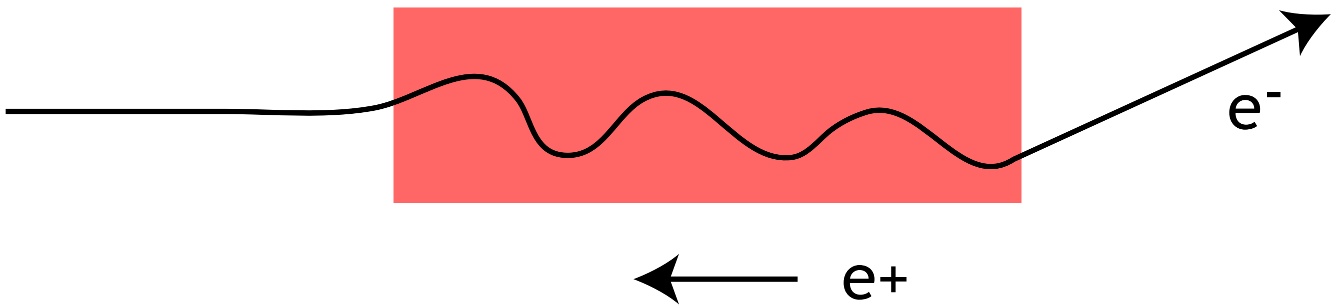
$$\beta = \frac{\alpha}{\pi}(\log\frac{s}{m_e^2} - 1) \sim 0.06 \qquad \text{at } 500 \text{ GeV}$$

Either the final electron or one of the radiated photons can be the initial parton in a hard-scattering process:



beamstrahlung:

at e^+e^- linear colliders, there is an additional source of radiation from a macroscopic effect, synchrotron radiation in the beam-beam interaction.



The characteristic parameter of synchrotron radiation is

$$\Upsilon = \gamma \frac{B_{eff}}{B_{crit}}$$

at typical LC conditions:

$$\Upsilon \sim \gamma \frac{1}{(m^2/e)} \cdot \frac{eN}{\sigma_z \sigma_\perp} \sim 1$$

so radiated photons have energy of the order of the e^- energy.

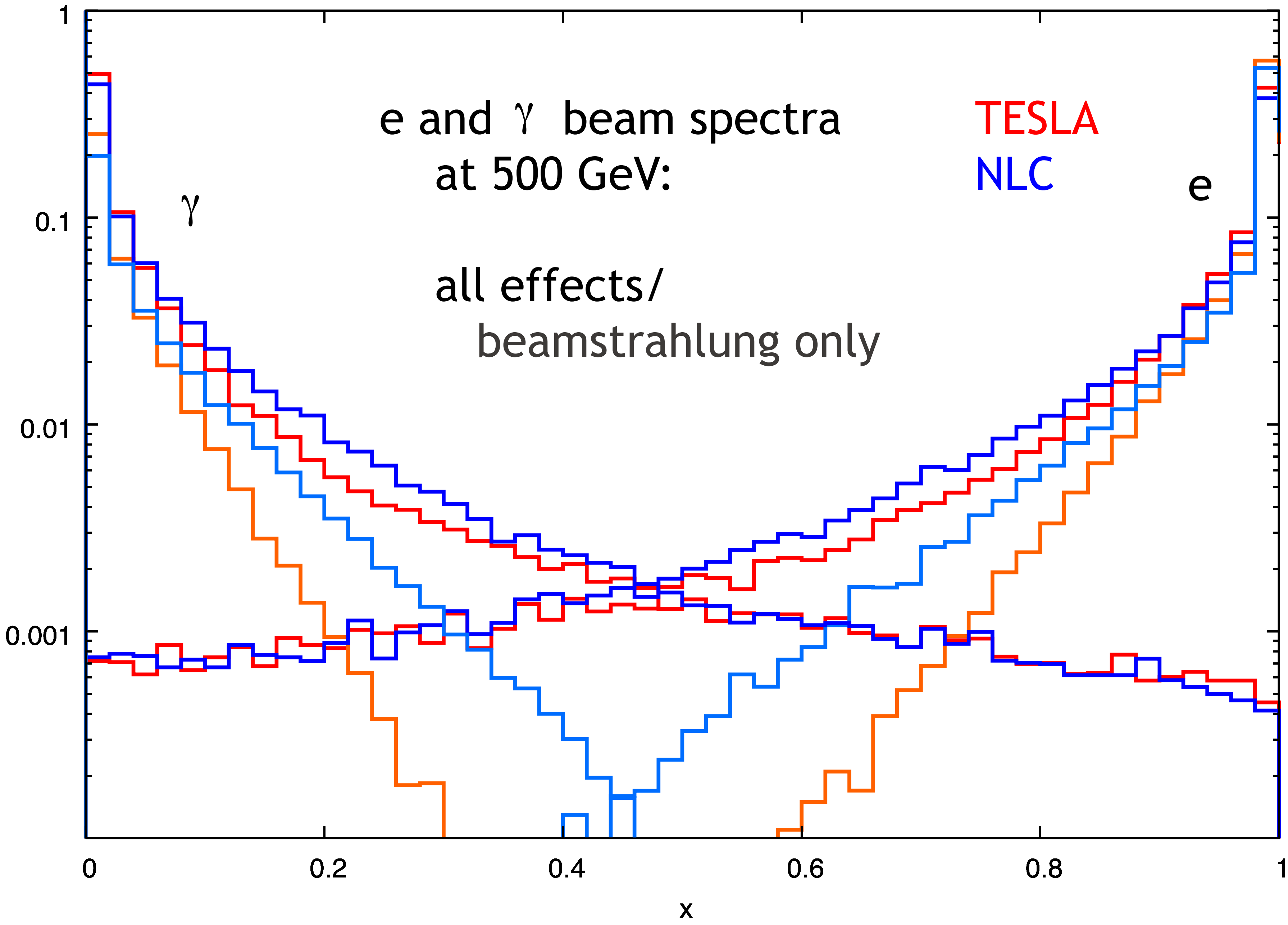
The electron spectrum after beamstrahlung has the form

$$f_e(x) = e^{-N_\gamma}\left[\delta(1-x) + \left(\sim \frac{e^{-2(1-x)/\Upsilon x}}{x^{2/3}(1-x)^{2/3}}\right)\right]$$

beamstrahlung depends on machine parameters;
modern designs use flat beams to minimize the effect

NLC/JLC and TESLA designs have beamstrahlung
of the same order as ISR.

but higher energy or luminosity requires higher beamstrahlung.



e and γ beam spectra
at 500 GeV:
TESLA
NLC
γ
e
all effects/
beamstrahlung only
1
0.1
0.01
0.001
0
0.2
0.4
0.6
0.8
1
x

ISR can be calculated precisely, but beamstrahlung, which depends on accelerator parameters and instantaneous luminosity, must be measured.

To monitor the e+e- luminosity spectrum, use high-rate, forward-peaked, SM processes:

$$e^+e^- \to e^+e^-$$

using acollinearity of final state e^+e^-

$$e^+e^- \to \gamma Z^0$$

using the opening angle of 2-lepton or 2-jet Z^0 final state

Now we are ready to add new physics. Many types of physics beyond the SM couple to fermion currents. These show up as new contributions to the e^+e^- annihilation amplitudes.

$Z^{0\prime}$ boson:

$$f_{LL} \rightarrow -Q + \frac{(-\frac{1}{2} + s_w^2)(I^3 - Q s_w^2)}{c_w^2 s_w^2} \frac{s}{s - m_Z^2} + \frac{Q'_{eL} Q'_L}{c_w^2} \frac{s}{s - M^2}$$

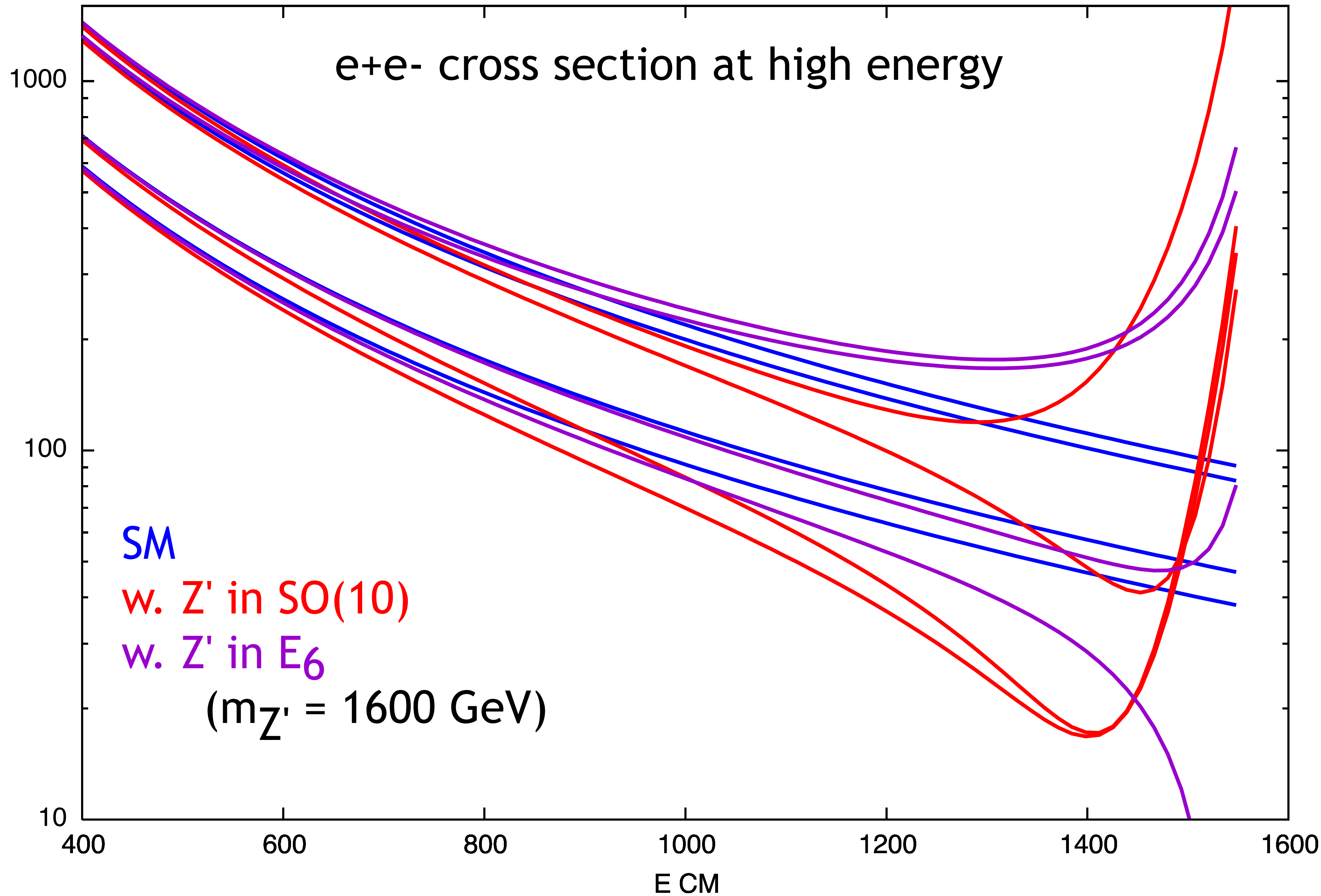
lepton and quark compositeness:

$$f_{LL} \rightarrow -Q + \frac{(-\frac{1}{2} + s_w^2)(I^3 - Q s_w^2)}{c_w^2 s_w^2} \frac{s}{s - m_Z^2} + \frac{\eta_{LL}}{\alpha \Lambda_{LL}^2} s$$

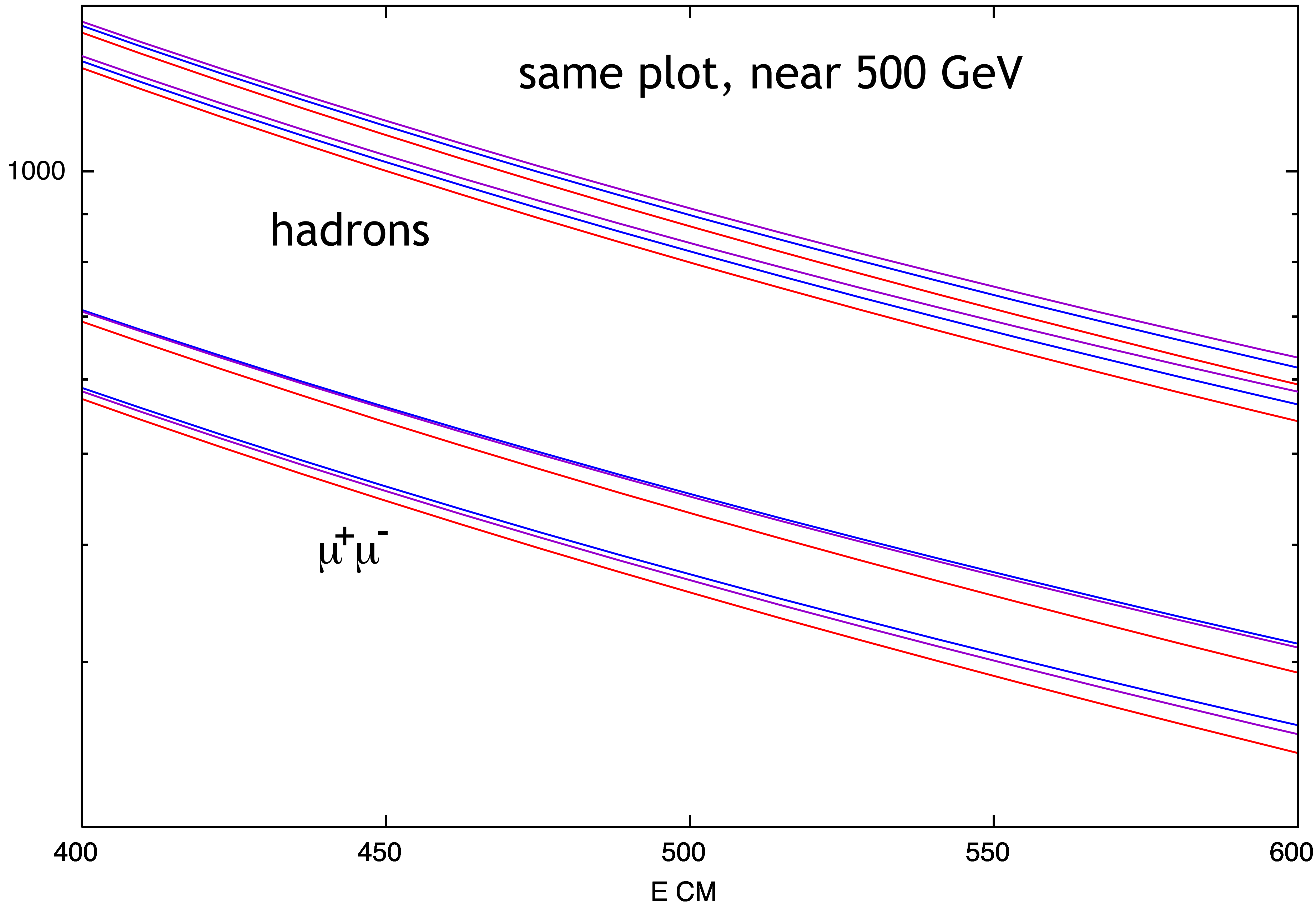
extra-dimensional graviton exchange:

$$f_{LL} \rightarrow -Q + \frac{(-\frac{1}{2} + s_w^2)(I^3 - Q s_w^2)}{c_w^2 s_w^2} \frac{s}{s - m_Z^2} + \frac{\lambda s^2}{4\pi\alpha M_H^4}(1 - 2\cos\theta)$$

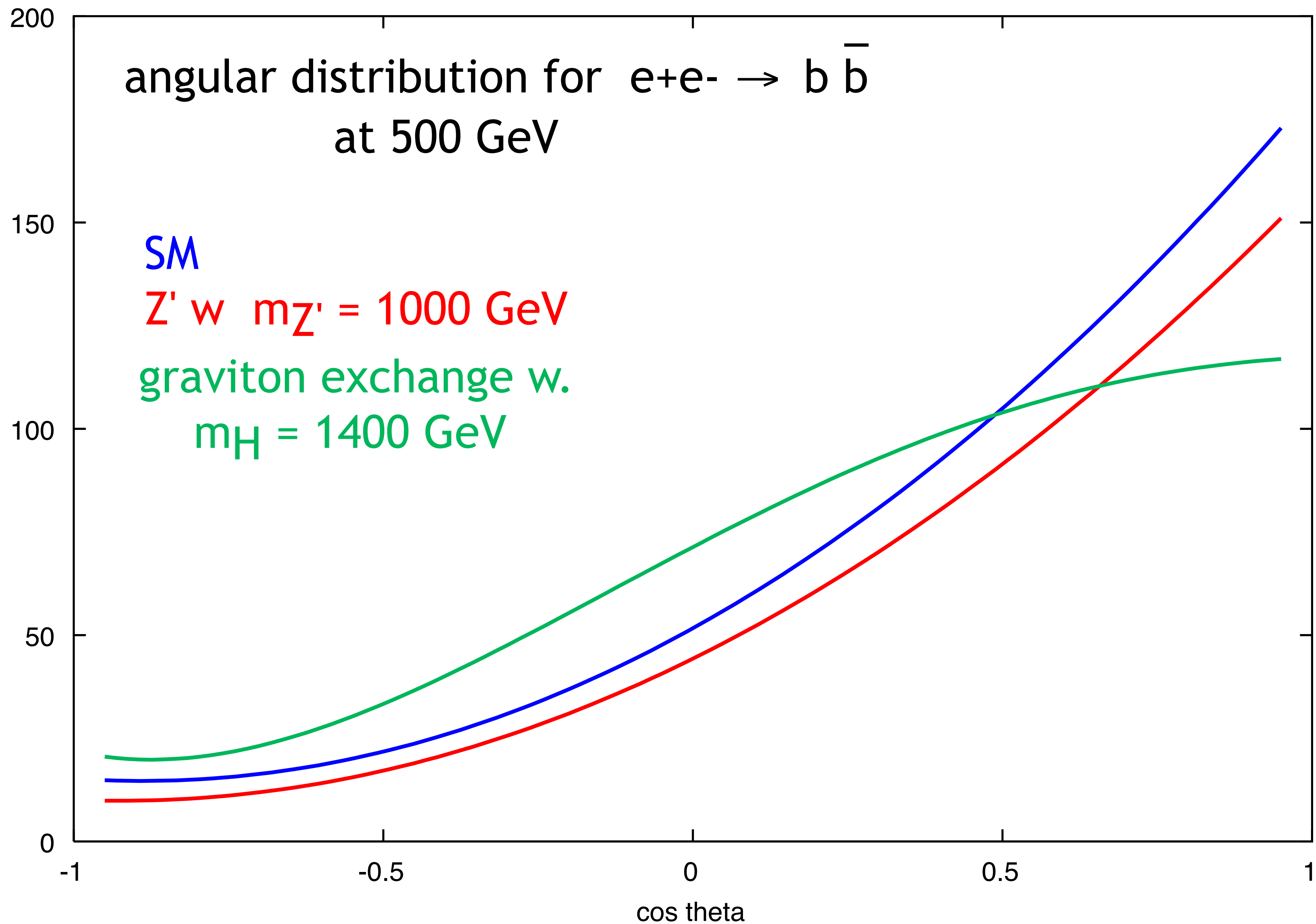
In most cases, either a resonance or a broad enhancement would have been seen at the LHC in qq scattering to lepton or jet pairs. The LC experiments would then diagnose the source of this efffect, studying its influence on each flavor and polarization state.



e+e- cross section at high energy
1000
100
10
400
600
800
1000
1200
1400
1600
E CM
SM
w. Z' in SO(10)
w. Z' in E6
(mZ' = 1600 GeV)



same plot, near 500 GeV
hadrons
$\mu^+\mu^-$
1000
400
450
500
550
600
E CM



angular distribution for e+e- → b $\bar{b}$
at 500 GeV
SM
Z' w $m_{Z'}$ = 1000 GeV
graviton exchange w.
m_H = 1400 GeV
200
150
100
50
0
-1
-0.5
0
0.5
1
cos theta

Massless fermion pair production is only the beginning of the LC story. Still within the SM, there are heavy particles - W and t - which can give new insights when studied with precision at the LC. We will analyze their properties in the next lecture.